

Maximal CP -Violation in Neutrino Mass Matrix in light of the latest Daya Bay result on θ_{13}

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Abstract

The Daya Bay Collaboration[1] has recently proclaimed discovery of non-zero reactor angle, θ_{13} , $\sin^2 2\theta_{13}=0.092\pm0.016(\text{stat})\pm0.005(\text{syst})$, at 5.2σ which is in conformity with the earlier observations of T2K[2], MINOS[3] and DOUBLE CHOOZ[4] last year. The discovery has immense implication for exploring CP -violation in the leptonic sector. In the present work, we examine CP -violation in Majorana neutrino mass matrix, in the basis where charged lepton mass matrix is diagonal, in which the ratio of elements are equal, also, termed as Strong Scaling Ansatz (SSA). This Ansatz has been known to explain the vanishing of θ_{13} and predict inverted hierarchy (IH) for the neutrino masses. However, to generate a non-zero value of θ_{13} consistent with Daya Bay result one has to deviate from SSA. This deviation will have important implications for CP -violation in the leptonic sector and is one of the issues addressed in the present work. CP is maximally violated because, for central value of θ_{13} obtained from Daya Bay experiment, Dirac-type phase $|\delta| \approx \frac{\pi}{2}$, $\frac{3\pi}{2}$ which corresponds to $|J_{CP}| \approx 0.03$. We have, also, studied imperative implications for Majorana-type phases α , β and effective neutrino mass, M_{ee} . The Majorana-type phases α , β are found to be sharply constrained.

The latest observation of reactor angle, θ_{13} , by the Daya Bay Collaboration[1] has, finally, proved that there are three kinds of neutrino oscillations. The global fits of three mixing angles at $1\sigma(3\sigma)$ C.L. are[5]

$$\theta_{12} = 34.0^{+1.0^{+2.9}_{-0.9}}, \theta_{23} = 46.1^{+3.5^{+7.0}_{-4.0}}, \theta_{13} = 7.27^{+1.65^{+4.12}_{-1.53}}. \quad (1)$$

The Daya Bay Collaboration[1] provide, at 5.2σ C.L., the value of mixing angle θ_{13} given by

$$\theta_{13} = 8.828^\circ \pm 0.793(\text{stat}) \pm 0.248(\text{syst}). \quad (2)$$

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Recently, there have been numerous theoretical and phenomenological attempts to explain the observed non-zero value of θ_{13} and to explore CP -violation in the leptonic sector[6]. Motivated by the recent measurement of θ_{13} , it will be of immense importance to investigate CP -violation in the leptonic sector seeing that the evidence of non-zero θ_{13} yields to a potentially measurable Dirac-type CP phase, δ , in future neutrino oscillation experiments. The present work is focussed on the issue of CP -violation in Majorana neutrino mass matrix, M_ν , with ratio of its elements being equal[7] and is given by

$$M_\nu = \begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{e\mu} & M_{\mu\mu} & M_{\mu\tau} \\ M_{e\tau} & M_{\mu\tau} & M_{\tau\tau} \end{pmatrix} \equiv \begin{pmatrix} A & B & B/s \\ B & D & D/s \\ B/s & D/s & D/s^2 \end{pmatrix}. \quad (3)$$

The Majorana neutrino mass matrix, M_ν (Eqn. (3)) has rank 2 and predict inverted hierarchy (IH) for the neutrino masses with $m_3 = 0$ and $\theta_{13} = 0$ indicating that there will not be any CP -violation in neutrino oscillation experiments. Therefore, in vista of Daya Bay results, one has to deviate from SSA to accommodate the non-zero value of $\theta_{13} = 8.828^\circ$ measured in Daya Bay experiment and to get a correct phenomenology. The Seesaw[8] realization of SSA and its implications for thermal leptogenesis have been discussed in Ref.[9]. The form (Eqn. (3)) necessarily occurs regardless of the form of right handed Majorana neutrino mass matrix, M_R , if third row of Dirac neutrino mass matrix, M_D , multiplied with s is equal to the second row[7]. The structure of Majorana neutrino mass matrix discussed in the present work has the additional virtue that it is stable against RG effects[7, 10]. Out of three possible independent scale invariant ways[7] only one (Eqn. (3)) is consistent with the current data on neutrino masses and mixings[7]. We establish deviations from SSA by introducing a scale breaking parameter κ in Majorana neutrino mass matrix and is given by

$$M'_\nu = \begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{e\mu} & M_{\mu\mu} & M_{\mu\tau} \\ M_{e\tau} & M_{\mu\tau} & M_{\tau\tau} \end{pmatrix}' \equiv \begin{pmatrix} A & B & B/s \\ B & D & D/s \\ B/s & D/s & D/(1+\kappa)s^2 \end{pmatrix} \quad (4)$$

where the parameters A, B and D are complex and s, κ are assumed to be real. To discuss the phenomenology of the model it is useful to note that Eqn. (4) yields three constraining equations which will be used to locate the parameter space of the model allowed by existing data on neutrino masses and mixing angles.

$$m_1 x + \tilde{m}_2 y + \tilde{m}_3 z = 0, \quad (5)$$

$$m_1 x' + \tilde{m}_2 y' + \tilde{m}_3 z' = 0, \quad (6)$$

$$m_1 x'' + \tilde{m}_2 y'' + \tilde{m}_3 z'' = 0, \quad (7)$$

where $\tilde{m}_2 \equiv m_2 e^{2i\alpha}$, $\tilde{m}_3 \equiv m_3 e^{2i(\beta+\delta)}$ and m_1, m_2 and m_3 are neutrino masses. The complex parameters $x, y, z, x', y', z', x'', y''$ and z'' are given by

$$\left. \begin{aligned} x &= U_{e1}(U_{\mu 1} - sU_{\tau 1}) \\ y &= U_{e2}(U_{\mu 2} - sU_{\tau 2}) \\ z &= U_{e3}(U_{\mu 3} - sU_{\tau 3}) \end{aligned} \right\}, \quad (8)$$

$$\left. \begin{aligned} x' &= U_{\mu 1}(U_{\mu 1} - sU_{\tau 1}) \\ y' &= U_{\mu 2}(U_{\mu 2} - sU_{\tau 2}) \\ z' &= U_{\mu 3}(U_{\mu 3} - sU_{\tau 3}) \end{aligned} \right\}, \quad (9)$$

$$\left. \begin{aligned} x'' &= U_{\tau 1}(U_{\mu 1} - s(1 + \kappa)U_{\tau 1}) \\ y'' &= U_{\tau 2}(U_{\mu 2} - s(1 + \kappa)U_{\tau 2}) \\ z'' &= U_{\tau 3}(U_{\mu 3} - s(1 + \kappa)U_{\tau 3}) \end{aligned} \right\}, \quad (10)$$

with

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}, \quad (11)$$

$$\equiv \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i(\beta+\delta)} \end{pmatrix}, \quad (12)$$

$c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$ [11]. Eqns. (5-7) can be written in terms of the ratios $\frac{\tilde{m}_2}{m_1}$, $\frac{\tilde{m}_3}{m_1}$ as

$$x + \frac{\tilde{m}_2}{m_1}y + \frac{\tilde{m}_3}{m_1}z = 0, \quad (13)$$

$$x' + \frac{\tilde{m}_2}{m_1}y' + \frac{\tilde{m}_3}{m_1}z' = 0, \quad (14)$$

$$x'' + \frac{\tilde{m}_2}{m_1}y'' + \frac{\tilde{m}_3}{m_1}z'' = 0. \quad (15)$$

Using Eqns. (13-14) the mass ratios $\frac{\tilde{m}_2}{m_1}$ and $\frac{\tilde{m}_3}{m_1}$ can be written as

$$\frac{\tilde{m}_2}{m_1} = -\frac{(c_{23}s_{12}s_{13} + c_{12}s_{23}e^{i\delta})(s_{12}(c_{23} + ss_{23}) - c_{12}s_{13}e^{i\delta}(c_{23}s - s_{23}))}{(c_{12}c_{23}s_{13} - s_{12}s_{23}e^{i\delta})(c_{12}(c_{23} + ss_{23}) + s_{12}s_{13}e^{i\delta}(c_{23}s - s_{23}))}, \quad (16)$$

$$\frac{\tilde{m}_3}{m_1} = \frac{c_{23}e^{i\delta}(s_{12}(c_{23} + ss_{23}) - c_{12}s_{13}e^{i\delta}(c_{23}s - s_{23}))}{(c_{23}s - s_{23})(-c_{12}c_{23}s_{13} + s_{12}s_{23}e^{i\delta})}. \quad (17)$$

The Taylor series expansion of mass ratios $\frac{m_2}{m_1}$, $\frac{m_3}{m_1}$ and the Majorana phases α , β upto first order in s_{13} can be written as

$$\frac{m_2}{m_1} = \left| \frac{\tilde{m}_2}{m_1} \right| \approx \left| 1 + \frac{s_{13}e^{-i\delta}(c_{23}(c_{23} + ss_{23}) + s_{23}e^{2i\delta}(s_{23} - c_{23}s))}{c_{12}s_{12}s_{23}(c_{23} + ss_{23})} \right|, \quad (18)$$

$$\frac{m_3}{m_1} = \left| \frac{\tilde{m}_3}{m_1} \right| \approx \left| \frac{c_{23}(c_{23} + ss_{23})}{s_{23}(c_{23}s - s_{23})} + \frac{c_{12}c_{23}s_{13}e^{-i\delta}(c_{23}(c_{23} + ss_{23}) + s_{23}e^{2i\delta}(s_{23} - c_{23}s))}{s_{12}s_{23}^2(c_{23}s - s_{23})} \right|, \quad (19)$$

$$\alpha \approx \frac{1}{2} \text{Arg} \left(1 + \frac{s_{13} e^{-i\delta} (c_{23} (c_{23} + s s_{23}) + s_{23} e^{2i\delta} (s_{23} - c_{23} s))}{c_{12} s_{12} s_{23} (c_{23} + s s_{23})} \right), \quad (20)$$

$$\beta \approx \frac{1}{2} \left(\text{Arg} \left(\frac{c_{23} (c_{23} + s s_{23})}{s_{23} (c_{23} s - s_{23})} + \frac{c_{12} c_{23} s_{13} e^{-i\delta} (c_{23} (c_{23} + s s_{23}) + s_{23} e^{2i\delta} (s_{23} - c_{23} s))}{s_{12} s_{23}^2 (c_{23} s - s_{23})} \right) + \delta \right). \quad (21)$$

Substituting the values of mass ratios $\frac{\tilde{m}_2}{m_1}$ and $\frac{\tilde{m}_3}{m_1}$ from Eqns. (18-19) in Eqn. (15) we obtain

$$\begin{aligned} & -c_{23} s_{12}^2 s_{23} - (1 + \kappa) s s_{12}^2 s_{23}^2 - \frac{c_{23}^2 (c_{23} (1 + \kappa) s - s_{23}) (c_{23} + s s_{23})}{(c_{23} s - s_{23}) s_{23}} - c_{12}^2 s_{23} (c_{23} + (1 + \kappa) s s_{23}) \\ & - \frac{c_{12} s_{13} e^{-i\delta} (c_{23}^2 (1 + \kappa) s + c_{23} (-1 + (1 + \kappa) s^2) s_{23})}{s_{12} (c_{23} s - s_{23}) s_{23}^2 (c_{23} + s s_{23})} \\ & + c_{12} s_{13} e^{-i\delta} \left(\frac{(1 + \kappa) s s_{23}^2 (s_{23} e^{2i\delta} (-c_{23} s + s_{23}) + c_{23} (c_{23} + s s_{23}))}{s_{12} (c_{23} s - s_{23}) s_{23}^2 (c_{23} + s s_{23})} \right) = 0. \end{aligned} \quad (22)$$

The real and complex part of Eqn. (22) can be written as

$$c_{23} s_{12} s_{23} (c_{23}^2 - \kappa s - c_{23} s_{23} - (1 + \kappa) s s_{23}^2) + c_{12} s_{13} (c_{23}^2 \kappa s - c_{23} s_{23} - \kappa s s_{23}^2) \cos \delta = 0, \quad (23)$$

$$c_{12} s_{13} (c_{23}^4 \kappa s - c_{23}^3 s_{23} - 2 c_{23}^2 (1 + \kappa) s s_{23}^2 + c_{23} s_{23}^3 + \kappa s s_{23}^4) \sin \delta = 0. \quad (24)$$

Solving Eqn. (23) and (24), for s_{13} and κ we obtain

$$s_{13} = -\frac{s_{12} s_{23}}{2 c_{12} c_{23} \cos \delta} \quad (25)$$

and

$$\kappa = \frac{c_{23} s_{23} (c_{23}^2 - s_{23}^2 + 2 s c_{23} s_{23})}{s (c_{23}^2 - s_{23}^2)^2} \quad (26)$$

Let us discuss the phenomenology of the Eqns. (18) and (25) to comprehend the interesting features of the correlation plots. For Eqn. (18) to be compatible with the solar neutrino mass hierarchy, the mass ratio $\frac{m_2}{m_1}$ should be greater than 1. If we put $\delta = \pi$ in Eqn. (18) we obtain

$$\frac{m_2}{m_1} \approx 1 - \frac{s_{13}}{c_{12} s_{12} s_{23} (c_{23} + s s_{23})} \quad (27)$$

which does not satisfy solar neutrino mass hierarchy. Also, $m_2 = m_1$ if $s_{13} = 0$ in Eqn. (18). Thus, the points $\delta = \pi$ and $s_{13} = 0$ are disallowed in neutrino mass models of the type given by Eqn. (4). In Fig. (1) we have plotted $R \equiv \frac{m_2}{m_1}$ as a function of (s_{13}, δ) and depict the parameter space (shaded region) for which solar

neutrino mass hierarchy is satisfied. Furthermore, it is implicit from Eqn. (25) that the Dirac-type CP violating phase δ should be in the II and III quadrant so as to make s_{13} positive definite i.e. $90^\circ < \delta < 270^\circ$. Thus, in light of the latest Daya Bay result on θ_{13} , Majorana neutrino mass matrix (Eqn. (4)) is necessarily CP violating (because $s_{13} \neq 0$ and $\delta \neq \pi$ implying $J_{CP} \neq 0$).

It is to be noted that we have not used these mass ratios (Eqns. (18-19)) and Majorana phases (Eqns. (20-21)) in our analysis which is completely based on the exact Eqns. (13-15). They are given here for the sake of illustration and to comprehend the interesting features of the correlation plots.

In our numerical analysis, we solve Eqns. (13) and (14) for two mass ratios $\frac{m_2}{m_1}, \frac{m_3}{m_1}$ and two Majorana phases α, β as a function of the other parameters of the model. All the known parameters are normally distributed with central values and errors given in Table 1. However, the parameters s and κ , which are the free parameters of the model, are uniformly distributed. Substituting the values of $\frac{m_2}{m_1}, \frac{m_3}{m_1}$ and two Majorana phases α, β in Eqn. (15), we look for the allowed parameter space for which Eqn. (15) is satisfied. We have illustrated the predictions of the model as correlations plots in Figs. (2-3) amongst various parameters of the model. To obtain the prediction of the model for θ_{13} we initially assume θ_{13} as free parameter giving full variation upto CHOOZ upper bound of 12° (left panel of Fig. (2) and Fig. (3)). The right panel of Fig. (2) depicts the impact of Daya Bay observation of non-zero θ_{13} , on the allowed parameter space and CP -violation. The strength of CP -violation in neutrino oscillations is described by the Jarlskog rephasing invariant[12] given by

$$J_{CP} = \Im[U_{e2}U_{\mu 3}U_{e3}^*U_{\mu 2}^*] = c_{12}s_{12}c_{13}^2s_{13}c_{23}s_{23}\sin\delta \quad (28)$$

In Fig. (2) we have depicted the correlation plots of κ, θ_{13} and J_{CP} . Fig (2(a)) has, previously, been obtained in Ref.[7]. However, here we want to point out that to generate a non-zero value of θ_{13} consistent with Daya Bay result requires a sizeable breaking of SSA which in Ref.[7] is termed as “weak scaling”. Thus, present data on neutrino masses and mixings allows only weak scaling in Majorana neutrino mass matrix. The correlation plots in the left column of figures have been obtained assuming θ_{13} as a free parameter, however, correlation plots in the right column of the figures shows the predictions of the model with θ_{13} given by Daya Bay experiment. In the second row of Fig. (2) the prediction for J_{CP} is shown as a function of the reactor angle, θ_{13} . It is implicit from the Fig. (2(d)) that the Majorana neutrino mass matrix model (Eqn. (4)) is necessarily CP -violating. Furthermore, it is rather interesting to find that CP is maximally violated as for best fit value of θ_{13} (Eqn. (2)), $|J_{CP}| \approx 0.03$ which corresponds to $|\delta| \approx \frac{\pi}{2}, \frac{3\pi}{2}$ which is large enough to be measured in future oscillation experiments.

Neutrinoless double beta decay ($0\nu\beta\beta$)[13] is an important low energy process which if observed, will establish the Majorana nature of neutrinos. The rate of this process is proportional to the modulus of (1,1) element of the effective Majorana neutrino mass matrix and is given by

$$M_{ee} = |\sum_i m_i U_{ei}^2| \quad (29)$$

which in terms of the mass ratios $\frac{\tilde{m}_2}{m_1}$ and $\frac{\tilde{m}_3}{m_1}$ can be written as

$$M_{ee} \approx \sqrt{\frac{\Delta m_{21}^2}{\left|\frac{\tilde{m}_2}{m_1}\right|^2 - 1}} \left(U_{e1}^2 + \frac{\tilde{m}_2}{m_1} U_{e2}^2 + \frac{\tilde{m}_3}{m_1} U_{e3}^2 \right). \quad (30)$$

In Fig. (3), we have shown the correlation plots of Majorana phases θ_{13} , α , β and effective Majorana neutrino mass M_{ee} . It is clear from Fig. (3(b)) that Majorana phase α (β) is sharply constrained to very narrow regions around -50° and 50° (-167° and -197°). We have, also, depicted correlation plot of M_{ee} with θ_{13} in Fig. 3 (c) (with θ_{13} as free parameter) and 2(d) (with $\theta_{13} = 8.828^\circ \pm 0.793(stat) \pm 0.248(syst)$). We obtain $M_{ee} = (0.046 - 0.066)\text{eV}$ which is within the range of future $0\nu\beta\beta$ experiments probing M_{ee} at the level of 10meV to 50meV[14, 15, 16, 17]. A non-observance of $0\nu\beta\beta$ decay down to the level of 0.046eV, which is achievable in future $0\nu\beta\beta$ experiments will rule out the Majorana neutrino mass model given by Eqn. (4).

In Conclusion, the experimental observations of non-zero θ_{13} by T2K[2] and, recently, by Daya Bay[1] experiment have triggered assiduous efforts to explore CP -violation in the leptonic sector. The Majorana neutrino mass matrix contain nine physical parameters and not all of them are measured by the neutrino experiments. Moreover, in Majorana neutrino mass matrix (Eqn. (4)), there are two more parameters s and κ making it arduous to solve analytically. In view of this, numerical approach to investigate the phenomenology of neutrino mass matrix is very imperative. In the present work, we have explored the CP -violation in the neutrino sector where the ratios of elements of Majorana neutrino mass matrix is equal (Eqn. (4)) and is, also, known as Strong Scaling Ansätz (SSA). We find that to obtain a value of θ_{13} , consistent with recent result of Daya Bay experiment for θ_{13} , require sizeable breaking of SSA. Thus, only weak scaling is allowed by current data on neutrino masses and mixings. Also, it is implicit from Fig. 2(d) that Majorana neutrino mass matrix (Eqn. (4)) is necessarily CP -violating. Furthermore, it is very interesting to find that CP is maximally violated as for best fit value of θ_{13} (Eqn. (2)), $|J_{CP}| \approx 0.03$ which corresponds to $|\delta| \approx \frac{\pi}{2}, \frac{3\pi}{2}$ and is large enough to be measured in future oscillation experiments. Majorana phase α (β) is sharply constrained to very narrow regions around -50° and 50° (-167° and -197°). We obtain $M_{ee} = (0.046 - 0.066)\text{eV}$ which is within the range of future $0\nu\beta\beta$ experiments probing M_{ee} at the level of 10meV to 50meV[14, 15, 16, 17]. A non-observance of $0\nu\beta\beta$ decay down to the level of 0.046eV, which is achievable in future $0\nu\beta\beta$ experiments will rule out the Majorana neutrino mass model given by Eqn. (4).

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Parameters	Best fit $\pm 1\sigma$ ($\pm 3\sigma$)
$\Delta m_{21}^2 [10^{-5} eV^2]$	$7.59^{+0.20(+0.60)}_{-0.18(-0.50)}$
$ \Delta m_{31}^2 [10^{-3} eV^2]$	$2.40^{+0.08(+0.27)}_{-0.09(-0.27)}$
θ_{12}	$34.0^{+1.0^\circ(+2.9^\circ)}_{-0.9^\circ(-2.7^\circ)}$
θ_{23}	$46.1^{+3.5^\circ(+7.0^\circ)}_{-4.0^\circ(-7.5^\circ)}$
θ_{13}	$7.27^{+1.65^\circ(+4.12^\circ)}_{-1.53^\circ(-5.45^\circ)}$

Table 1: The global fit of the neutrino mixing angles and mass-squared differences at 1σ (3σ) confidence levels.

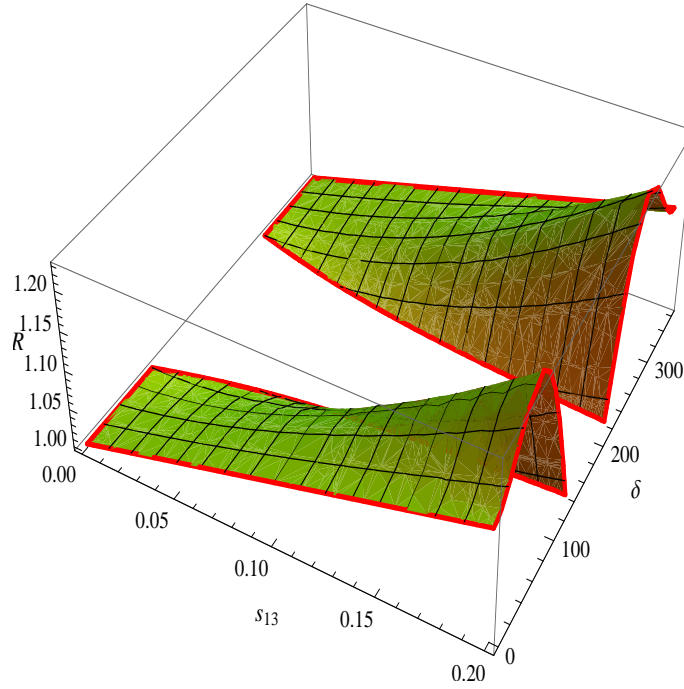


Figure 1: $R_1 \equiv \frac{m_2}{m_1}$ as a function of s_{13} and Dirac-Type CP violating phase δ .

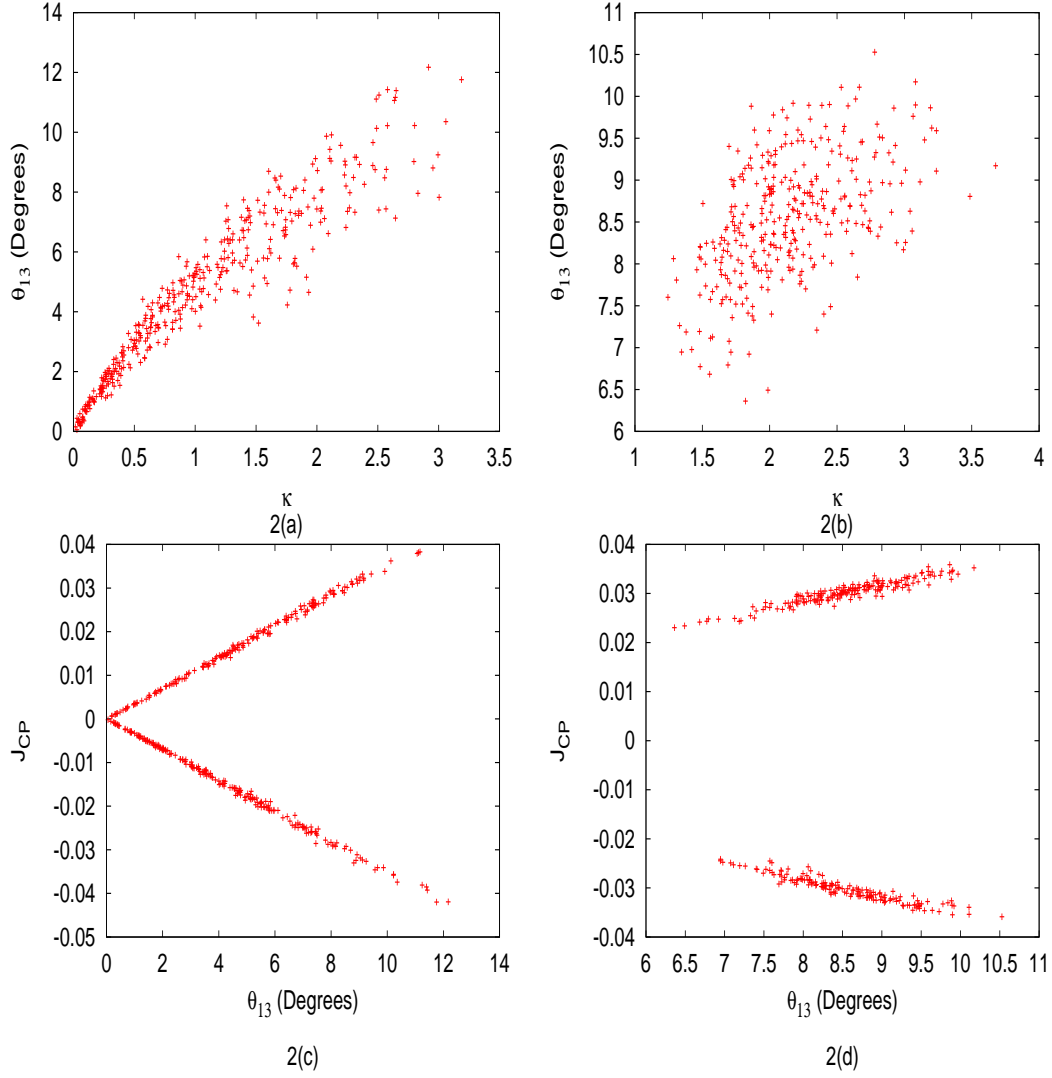


Figure 2: The correlation plots of κ , θ_{13} and J_{CP} for inverted hierarchy (IH) of neutrino masses. The left (right) panel is without (with) Daya Bay result for θ_{13} .

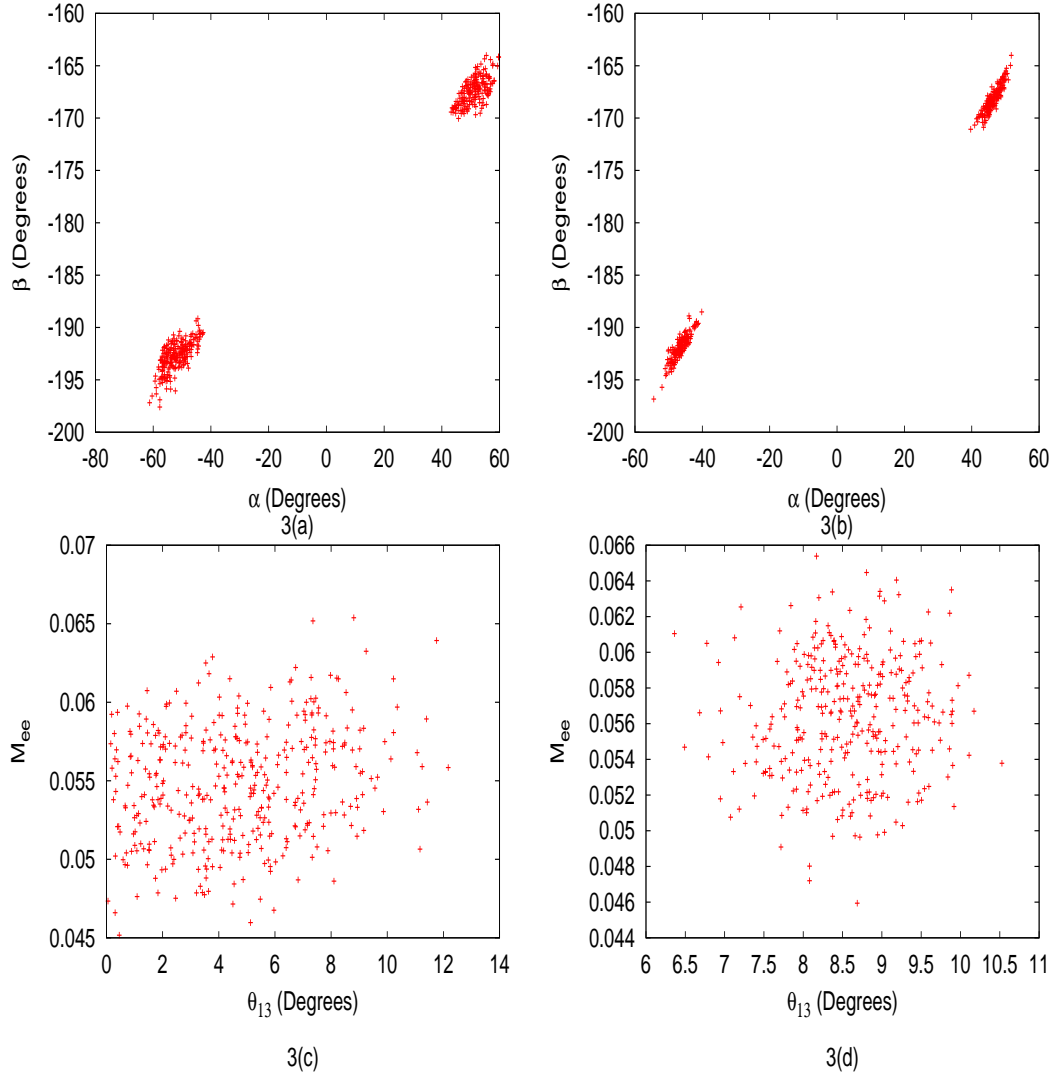


Figure 3: The correlation plots of Majorana phases α , β , θ_{13} and effective Majorana neutrino mass M_{ee} (eV) for inverted hierarchy (IH) of neutrino masses. The left (right) panel is without (with) Daya Bay result for θ_{13} .